Morris, KA., & Kenington, PB. (1998). A broadband linear power amplifier for software radio applications. In *Vehicular Technology Conference, VTC'98* (Vol. 3, pp. 2150 - 2154). Institute of Electrical and Electronics Engineers (IEEE). https://doi.org/10.1109/VETEC.1998.686138

A Broadband Linear Power Amplifier for Software Radio Applications

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Abstract - This paper discusses a new type of polynomial-based RF predistorter with excellent broadband performance and very low levels of complexity. The technique employed here may be designed to operate at any desired centre frequency and therefore has application in the PMR, cellular and satellite areas of communications systems. The technique is compact, very simple and of very low cost, so it will find application in handsets as well as within the base station environment.

I. Introduction

Software radio has been recognised as the next major leap forward in mobile communications, particularly in the light of the many existing world-wide air interface standards and the wide range of future proposals for UMTS [1,2]. The convergence of mobile satellite and terrestrial cellular technologies inevitably leads to the requirement for a combined handportable terminal. At present this is envisaged as a dual-mode, or even a dual radio handset, due to the difficulties in achieving a satisfactory performance from shared RF hardware and flexible DSP processing.

A software radio (also called a 'flexible architecture radio') is a transceiver in which, ideally, all aspects of its operation are determined using reconfigurable elements. This is usually thought of in terms of baseband DSPs, but FPGAs and other techniques are also possible. It is also usually assumed to be broadband in nature, as one of its principal applications is perceived to be in replacing the numerous handsets currently required to guarantee cellular (and in the future, satellite) operation world-wide. This is strictly speaking an extension of the basic 'software radio' concept into that of a broadband flexible architecture radio, since the reprogrammability and adaptability aspects of operation do not depend upon multi-band coverage. It would be possible, for example, to construct a useful software radio which operated in the 800/900MHz area of spectrum and which could adapt between TACS, AMPS, GSM, DAMPS, CT2 and PDC. The trend is, however, for multi-frequency operation (there are emerging handsets which cover both GSM and DECT, generally by employing separate RF hardware for each, in a common case).

There are many issues which must be addressed in determining if a software radio is realistic and also to what extent it is flexible. Coping with wider channel bandwidths and operating in multiple bands in differing parts of the spectrum is much more difficult, but nevertheless essential for a combined terrestrial/satellite telephone.

The essence of a software radio is to be instantly configurable to any desired present or future mobile radio standard. This means that the components used in its construction must be frequency independent and independent of the modulation scheme employed. The RF section must therefore be capable of operation over a wide frequency range and with a wide channel bandwidth. It must also be transparent to the modulation scheme being employed, thus implying some form of linear amplification to allow high rate multi-level modulation schemes to be accommodated.

In considering which amplification method to use, the requirement for a broadband wide frequency range system implies that a feedback based technique is unlikely to be applicable. In particular, if high degrees of linearity are required, then even modulation feedback systems, such as Cartesian Loop, are not generally capable of the required channel bandwidth *and* linearity improvement simultaneously.

Feedforward systems are one obvious alternative, however although giving a high level of linearity, they provide poor levels of efficiency when compared to other systems. For example, a class C amplifier can operate with an efficiency of 60% but the same amplifier employed in a feedforward system (assuming no losses) will have an efficiency of only 42% (assuming a similarly efficient error amplifier); a significant reduction. It has been proposed that to improve the efficiency of a feedforward system a simple RF predistorter is fitted to the amplifier and then feedforward correction applied to give a high level of linearity. If the theoretical efficiency of such a system is calculated as before, then the overall efficiency of the

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0-7803-4320-4/98/$5.00

improvement the theoretical efficiency improves to 57%, which is almost the same as for the original amplifier.

II. Predistortion Systems

RF Predistortion is one of a number of techniques which may be used to linearise RF power amplifiers. It has the advantage of excellent broadband performance when compared to other techniques and a very low efficiency penalty, making it an excellent compliment to feedforward. This fact makes a predistorter an ideal addition to a feedforward amplifier system in order to improve efficiency.

Predistortion has the advantage of a lower efficiency penalty when compared with feedforward linearisation techniques, whilst still retaining the potential of excellent broadband operation. This fact makes a predistorter an ideal addition to for example a feedforward amplifier system in order to improve efficiency and reduce the overall complexity of the complete system. and may be divided into two broad categories: baseband predistortion and RF based predistortion techniques. RF predistortion may be further subdivided into generic and polynomial based predistorters. The approach adopted was to develop a polynomial predistorter which may be used for the broadband linearisation of an RF power amplifier. The technique employed here may be designed to operate at any desired centre frequency and therefore has application in the PMR, cellular and satellite areas of communications systems. The technique is compact, very simple and of very low cost so that it may be used in handsets as well as within the base station environment.

Predistortion is one method of achieving broadband linearisation of RF power amplifiers [3]. The method in its simplest form uses a non linearity which has the inverse transfer characteristic of the amplifier being linearised. The non linearity may be either of the generic type [4] which provides a true inverse of the amplifier transfer function or of the polynomial type [5] which provides an approximation of the transfer function in terms of polynomial terms [6]. A block diagram of a predistortion system is shown in figure 1 below.

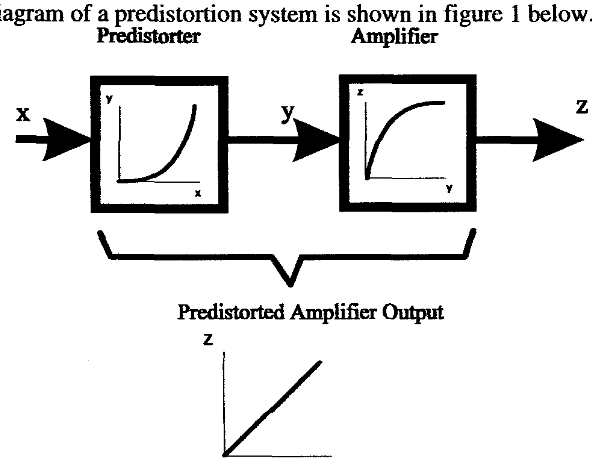

Figure 1: Predistortion System Block Diagram

III. 3rd Order Polynomial Predistortion

The predistortion system designed here was of the scalar type: which acts on the amplitude to amplitude (AM to AM) and the amplitude to phase (AM to PM) distortion together. With reference to figure 2 the predistorter operates as follows: the RF signal is split at the input to of the system into fundamental and predistorted parts. The fundamental path contains an attenuator and also sufficient delay to equal the delay in the predistorted path. This balancing of delay is important when achieving broadband cancellation of intermodulation products. The predistorted path consists of a cubic element (3rd order non-linearity), amplitude and phase control and a buffer amplifier. The cubic element provides the expansive characteristic necessary to counteract the compressive characteristic of the amplifier and thus improving the linearity of the overall system. The amplitude and phase control elements are used to control the amplitude and phase of the cubic terms to achieve optimum cancellation of distortion products, they are voltage controlled so that if desired the system may be controlled automatically. The buffer amplifier which follows is used to amplify the predistortion components due to the significant attenuation introduced by the cubic element.

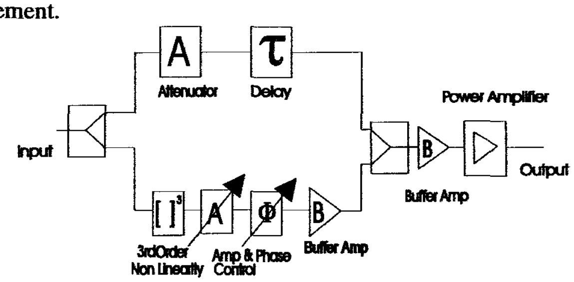

Figure 2: 3rd-Order Polynomial Predistortion System

The resulting output from the cubic non linearity is shown in figure 3 overleaf, this test being carried out at a centre frequency of 900MHz and a tone spacing of 500kHz. The actual frequency used for the test is unimportant since similar results have been achieved for any frequency within the element's operating range of 100MHz to 1GHz. The plot clearly shows that the characteristic is symmetrical and that the 3rd order intermodulation products (IMP's) are present. Also however there are 5th, 7th, 9th and 11th order IMP's, these being due to additional, undesirable, non-linearity within the cubic element. These additional products will degrade the theoretical cancellation of the 3rd-order IMP's to some extent. This degradation will result in a slight increase in the higher-order products. The actual practical implications of this will be discussed later. The graph also shows that the actual power levels are fairly low, this is overcome by fitting a buffer amplifier in the predistorted path. Apart from the undesirable higher-order terms, the original fundamental terms are also present. This is unimportant since the fundamental terms which pass through the main path will be the dominant driving terms.

Figure 2 shows that the fundamental and predistorted paths are power combined via a hybrid combiner and then buffer amplified. The result of this combining and amplification is shown in figure 4, it may be seen that this is in effect a multi-tone test with the main tones at -9dBm and the 3rd-order IMP's at 24dB below the main tones.

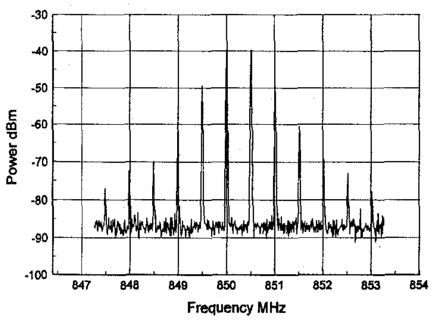

Figure 3: Cubic Non Linearity Output

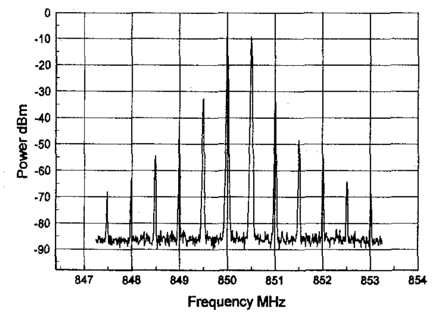

Figure 4: Predistorted Input to Main Amplifier

Ideally the predistorter provides a good inverse transfer function of the amplifier being linearised, the effects of any deviation from the ideal inverse may be seen by applying a two tone test and observing the output spectrum of the now linearised amplifier. In order to achieve this the predistorter needs to be set up correctly. The difference between the main-tone and 3rd order IMP energy is important in achieving the best possible cancellation. The ratio of main-tone energy to 3rd order IMP energy at the predistorter output needs to be the same as the ratio of the main-tone to third order IMP energy which is given by the amplifier two tone test. The two tone test is also the means by which the improvement in performance achieved by the predistortion technique may be gauged. At 850MHz the two tone test and the predistorted amplifier output is shown in figures 5 and 6. Figure 6 shows that the 3rd order IMP's are now at -44dBc, this is an 18dB improvement in performance over the two tone test. The 5th and 9th order IMP's have increased however, this is due to the generation of these undesirable terms by the cubic non linearity. Normally an amplifier linearity is specified in terms of the ratio of the highest power IMD products to the fundamental terms, this means that the linearity has been significantly improved when compared to the uncompensated case.

The predistortion system which has been developed can linearise an amplifier using the same hardware at any operating frequency over the range of 100MHz to 1GHz. Linearisation of the amplifier has been achieved over this range with the results being shown for frequencies of 100MHz and 1GHz in figures 7, 8, 9 and 10.

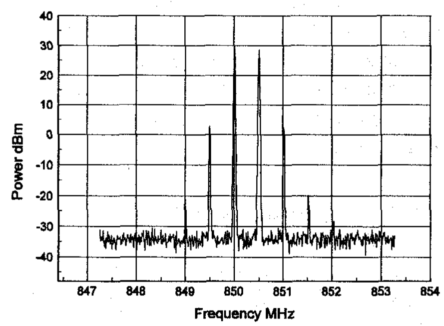

Figure 5:TwoToneTest at 850MHz

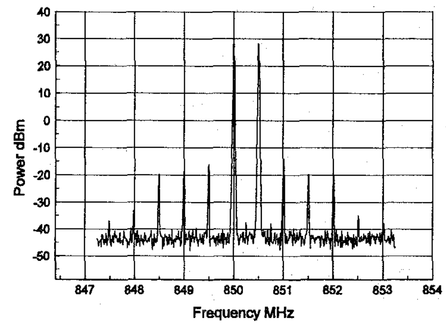

Figure 6: Predistorted Output Amplifier Output at 850MHz

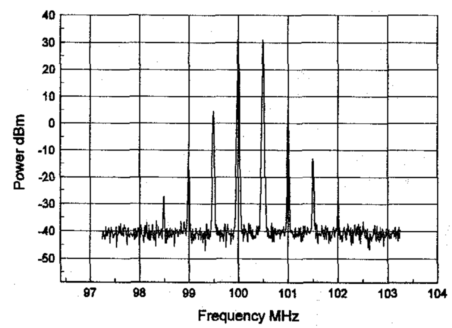

Figure 7: Two Tone Test at 100MHz

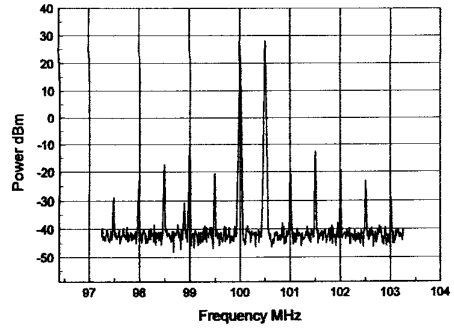

Figure 8:Predistorted Amplifier Output at 100MHz

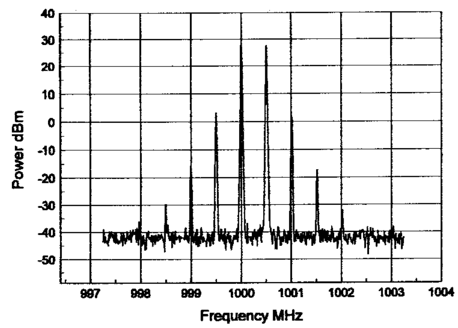

Figure 9:Two Tone Test at 1GHz

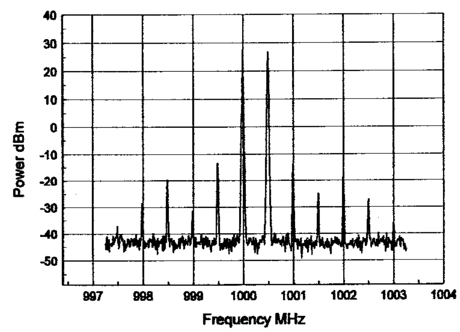

Figure 10: Predistorted Amplifier Output at 1GHz

Figure 8 shows the results at 100MHz, the plot shows that the 3rd order products are at -49dBc. The higher order products are not affected so the overall specification improvement is 25dB. Figure 10 shows that at 1GHz the 3rd order IMP's are at -41dBc, another significant improvement over the unpredistorted two tone test case. The 5th order products in this case have actually reduced so the 3rd order products are the largest IMP's, giving an overall specification improvement of 15dB.

A. Wideband Measurements

The results in the previous section were taken without the system being optimised for use at very wide bandwidths. When designing the system it is very important to ensure that the delays of the fundamental path and the predistorted path are carefully matched if true broadband performance is required. investigations have shown that errors of greater than +/- 0.05λ will result in significant degradation of performance over bandwidths greater than 2MHz. Tests have been conducted with the system at 900MHz with tone spacings of 30MHz and 60MHz the results of these tests are shown below in figures 11, 12, 13 and 14.

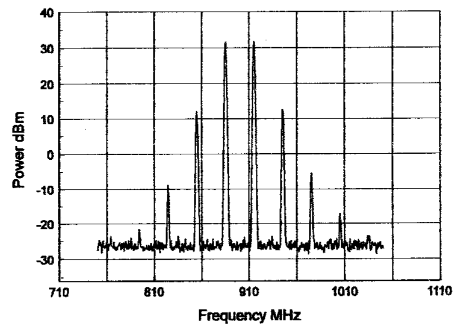

Figure 11: Two Tone Test at 30MHz Tone Spacing

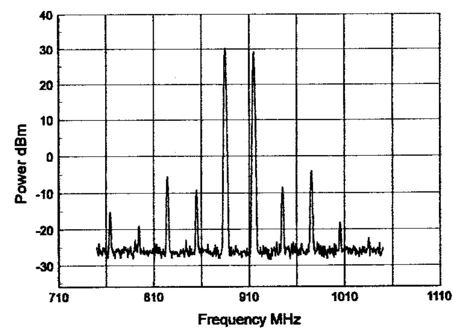

Figure 12: Predistorted Amplfier Output at 30MHz Tone Spacing

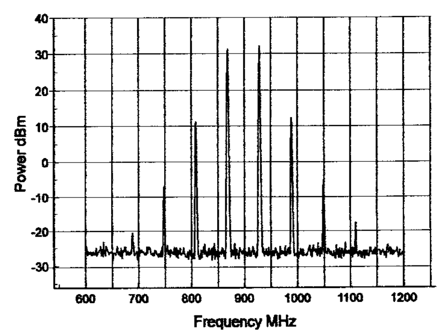

Figure 13: Two Tone Test at 60MHz Tone Spacing

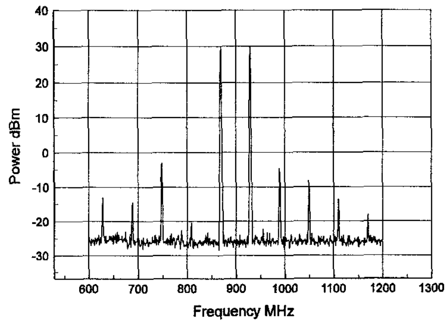

Figure 14: Predistorted Output at 60MHz Tone Spacing

With reference to figures 11 and 12 it can be seen that the 3rd order IMP's are at -38dBc an improvement of 18dB over the uncompensated case, however the 5th order products have increased so the overall improvement in specification is 14dB which is a slight reduction over the 3rd order IMP case alone. Referring to figures 13 and 14 it can be seen that the 3rd order products are at -35dBc, giving an improvement of 15dB when considering the 3rd order IMP's alone. If the 5th order products are considered however, they have again increased resulting in an overall specification improvement of 12dB. This is very significant when considering that this has occurred at an instantaneous bandwidth of 180MHz.

The performance of the prototype system is outstanding: it is capable of providing 15dB of IMD improvement (from –25dBc to –40dBc) across an operational bandwidth extending from 100MHz to 1GHz (i.e. a decade of frequency) *with the same hardware.* The maximum instantaneous channel bandwidth capability is 180MHz anywhere within the above frequency range. The elements used within the predistorter are broadband, general purpose devices and hence the technique may be extended to higher frequencies and possibly also to wider instantaneous bandwidths. The elements are also generic and hence do not require special selection or fabrication for a particular amplifying device or technique.

IV. Conclusions

This paper has clearly shown that polynomial predistortion has the potential to provide useful improvements in amplifier linearity. Improvements being achieved over a very wide frequency range: 100MHz to 1GHz using the same hardware. By careful design and balancing of delays it is possible to linearise over very wide bandwidths indeed, tests being conducted at upto 180MHz instantaneous bandwidth. Although tests were carried out at upto 60MHz tone spacing there is no reason to believe that wider bandwidths are not achievable. Due to the relative simplicity of this hardware this method of predistortion may well find application in both the basestation and the mobile part of a radio communication system.

Single order polynomial predistortion in general is suitable for use in systems with predominantly single order non linearity (usually third-order). For systems with more than one order of non linearity then a multiple order polynomial predistorter would be required. Polynomial predistortion as demonstrated here has application in satellite systems where the linearity improvement required is small, typically 5 to 10dB. The results show that this system could easily meet this specification.

Acknowledgments

The authors would like to thank Professor J. P. McGeehan for the provision of laboratory facilities. The first author would also like to thank EPSRC for funding this work.

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